ASM:
scaled down Active Segmented Mirror developed to simulate a segmented primary mirror

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ABSTRACT

The Active Segmented Mirror is a key subsystem of the Active Phasing Experiment. The size of the ASM is 154 mm in diameter. It will be used to test new types of phasing sensors recently developed within the ELT design study supported by the European Union. To our knowledge it is the first time that such miniature active optics composed of hexagonal segments having 3 degrees of freedom with a resolution of the order of a few nanometers and a range of several micrometers is manufactured. The ASM is composed of 61 hexagonal segments called "modules". Each module is assembled, glued and integrated from standard (piezo-actuators) and custom-made (mirrors, mechanics) parts procured from industries. The ASM has been designed and integrated at the European Southern Observatory. Specifications, designs, assembly tools, hand work skills, electronics, software, control algorithms and test procedures are the field of competences required to obtain in the end a "plug and play" product. The concept of the ASM is tested and validated by a prototype version composed of 7 modules equivalent of the central area of the ASM itself. The design, integration and results of the ASM tests are presented.

Keywords: ESO, ASM, APE, ELT, hexagonal segments, segmented mirror, development, scaled down, active optics.

1. INTRODUCTION

Segmented primary mirror is mandatory for the design of the future **E**uropean **E**xtremely **L**arge **T**elescope (EELT). Such facility needs a new type of telescope control system taking account of the phasing of the primary mirror. The **A**ctive **P**hasing **E**xperiment[1,2] (APE) has been developed to explore future technologies for the phasing sensors and study new telescope control systems. The key subsystem to simulate primary segmentation in APE is the **A**ctive **S**egmented **M**irror (ASM). The ASM is composed of 61 flat hexagonal mirrors 17 mm side to side and with a gap in-between of 100 µm. The size of the segments and the distance between two mirror edges are approximately 100 times smaller than of an ELT. Each segment of the ASM is controlled in Piston, Tip and Tilt by means of piezo actuators having a stroke of 30 µm. The whole optical surface is inscribed inside a diameter of 154 mm and allows a non-vignetted beam footprint of 130 mm.

A prototype composed of 7 modules (one mirror fully surrounded by its six neighbours) has been developed to validate the concept, the performances, the integration steps, the tooling and the verification approach. The performance of this prototype with the nominal control electronics has been tested and compared to the requirements. This approach minimizes the development risk for the final system, requested for the project.

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2. REQUIREMENTS

The key requirement for the ASM is to be representative to an ELT, at a scale affordable for laboratory testing and VLT UT nasmyth platform sizes. Therefore, the ASM main characteristics are settled as follows:

- Free optical aperture of 130 mm
- 61 protected aluminum flat mirrors with a surface flatness better than 15 nm RMS
- Segments with hexagonal shape, 17 mm width side to side, low thermal expansion glass, sharp edges.
- Gap of 100 µm between two segments.
- Active control over a maximum range of 15 µm for Piston, Tip and Tilt.
- Frequency response ≥ 10 Hz
- Used in laboratory and at telescope environment.

3. CONCEPT AND DESIGN

3.1 Concept of the ASM into the Active Phasing Experiment

APE is developed to validate wavefront control concepts for the EELT. It will be mounted at a nasmyth focus of a VLT at Cerro Paranal (Fig. 1). It contains four different types of **P**hasing **W**ave**f**ront **S**ensors (PWFS). APE will be fully tested in laboratory first, prior installation on the telescope.

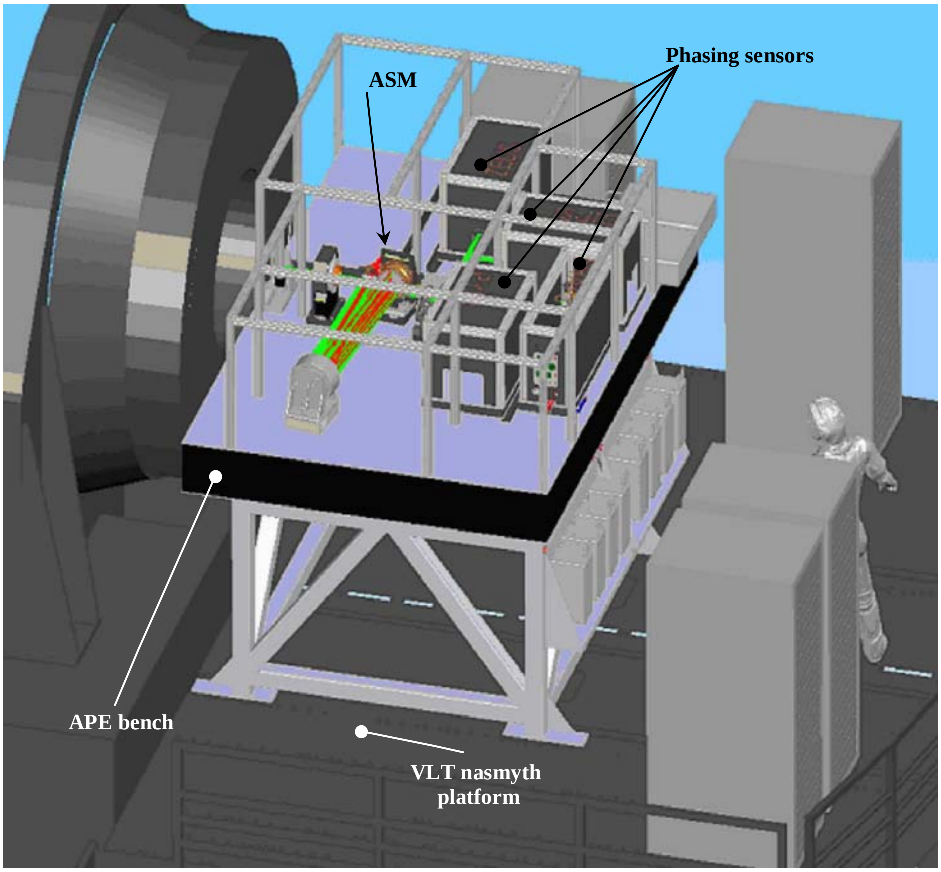

Fig. 1: ASM into APE on a VLT nasmyth platform

The segmentation of a primary mirror is simulated by imaging the pupil of the VLT telescope onto the ASM.

As shown in Fig. 2, the design of the ASM take into account all the requirements mentioned above, mass production of the mirrors segments and maintainability during lifetime.

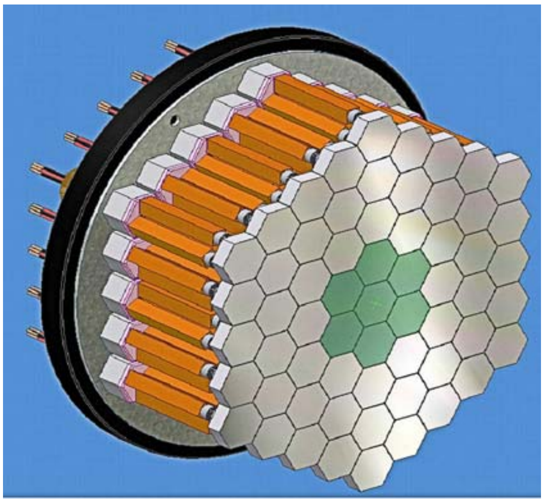

Fig. 2: Preliminary ASM concept showing that a prototype version was foreseen at early concept phase

In-house design and -development of the ASM was the selected approach, because it presents the advantage of interchangeable modules and the experience gained regarding manufacturing of segmented mirrors.

Baseline of the design was to use as far as possible simple interfaces, to assure the modularity of the elements and to use out off the shelves components.

3.2 Module description

The ASM is an assembly of 61 Modules shown in Fig. 3. The CAD design of the module was consolidated by FEM analysis. In parallel to the ASM module design, the specific assembly tools were developed to ease the integration and later the tests.

Each module is composed of a base where three piezo actuators are mounted. On top of each piezo actuator, a mirror support element (spring) interfaces the mirror segment made of Zerodur®. The three piezo actuators provide the Piston, Tip and Tilt movement required.

Fig. 3: Single module concept

3.3 ASM mount description

A specific mount (Fig. 4) is used to hold and align the ASM on the bench. Tip and Tilt of the ASM are done with rotating axis located above the main base and as close as possible to the optical surface to respect the gimbal principle. Lateral alignment is carried out with adjustable stops that will be locked when aligned. Vertical alignment is adjusted by shims. The front cylinder allows attachment of alignment tools and telescope spider masks.

The ASM is located in a pupil plane that is “materialized”, in position and in orientation around the optical axis, by single mode fibers glued trough central and top mirrors.

Fig. 4: ASM mount with prototype

3.4 ASM mechanical analysis

The Finite Element analyses concentrates on the Eigen mode of the module, the static displacement, stress introduced at mirror back surface at maximum elongation of the piezo actuator.

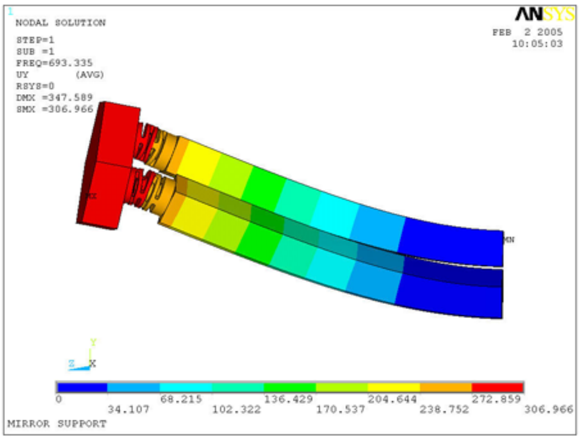

Fig. 5: 1st mode and natural frequency

The modal analysis was made for the first 40 natural frequencies and modes using Block Lanczos algorithm. The first natural frequency occurs at 693 Hz and represents a bending mode shape in y-direction (Fig. 5).

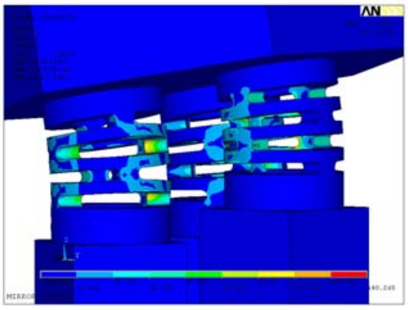

Fig. 6: Detail of Von Mises stresses in the springs

The mirror is shifted laterally by about 35 µm when one piezo is elongated at maximum stroke of 30 µm. Stress introduced in the spring remains under acceptable value.

Fig. 6 shows the static displacement and the stresses introduced at spring level.

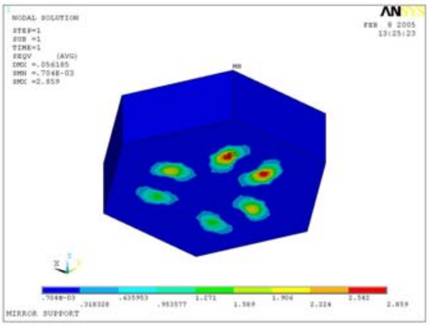

Fig. 7: Detail of Von Mises Stresses in the mirror

As shown in Fig. 7, stress introduced in the mirror back surface for the maximum elongation is estimated around 2.9 Mpa (Von Mises). This value is within the acceptable tolerance for the selected glass material.

These three analyses guarantee that the selected design options and material selections are compatible with the survival loads and fulfill the specifications.

3.5 ASM Control and Control Electronics

The control design concept of the ASM has a cascade structure, where in the inner-loop the position of the segment is measured by the **I**nternal **M**etrology[3] (IM) and so its feedback generates via a controller an appropriate input command to piezo actuators. In the outer-loop, based on the wavefront sensor measurements[1,2], the desired references for the inner-loop are generated. The cascade control structure is depicted in Fig. 8.

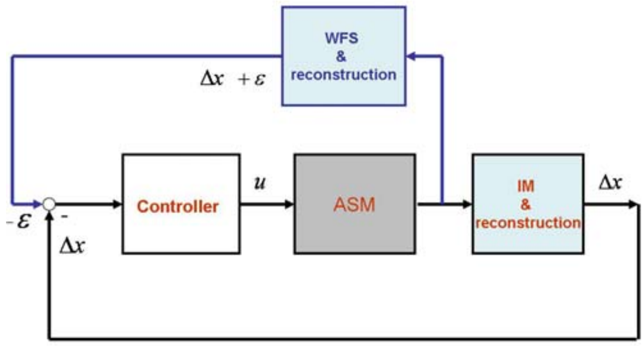

Fig. 8: ASM Module control block-diagram

The measurements data for the inner-loop are available at a rate of 8 Hz and for the outer-loop at a slower rate of 0.03Hz. The sampling frequency for the inner-loop control is governed by the measurement system (IM). Since the control is implemented digitally, a digital controller for the module is designed, where the sampling frequency is set to 8Hz. The control objective is to track the reference coming from the outer loop or an external reference generator and compensate for quasi-static perturbations. The main requirement for control is to guarantee reference tracking (positioning) with a zero permanent error.

Based on the model, a Proportional Integral control is designed. The closed-loop bandwidth is set to 0.5 Hz. The pole/zero of the closed-loop system and the loop transfer function together with the stability margins are shown in Fig. 9. The closed-loop transfer function is depicted in Fig. 10.

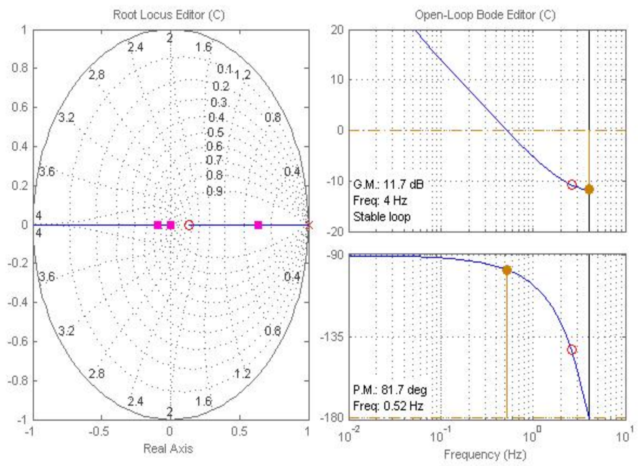

Fig. 9: Loop transfer function: Phase margin = 81.7 deg, Gain margin =11.7

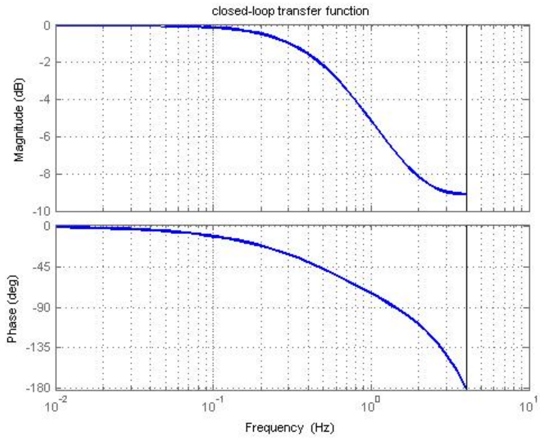

Fig. 10: Closed-loop transfer function

The closed-loop response of the system for a step reference signal of 1 μm is simulated and showed in Fig. 11. In this case the dynamics and noise of the IM sensor is not included. It can be seen that the system tracks the reference signal perfectly without any permanent error and overshoot.

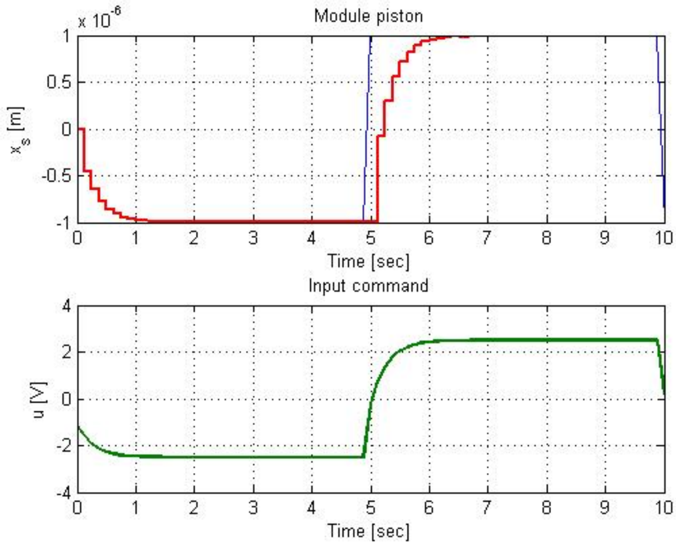

Fig. 11: Closed-loop response of module piston to a step reference=1 micro-meter, integral control

The block diagram of the control electronics requested to drive the Piston, Tip and Tilt of each segment measured by the Internal Metrology is shown in Fig. 12. The piezo stroke positions for each ASM segment are commanded by the ASM Local Control Unit. The Digital In/Output drives the 40 Bit width data bus, which is used to control the High Voltage Amplifiers. The High Voltage is then distributed to the piezo actuators of the ASM.

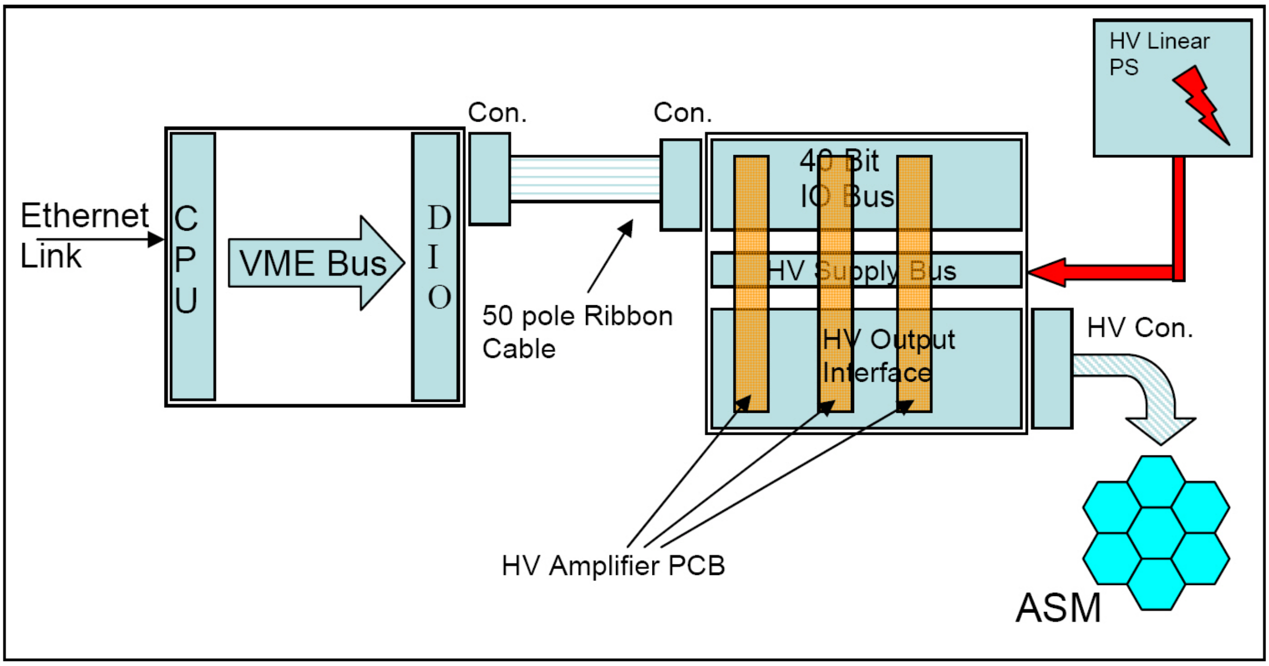

Fig. 12: Control electronics for the ASM

4. PROTOTYPE AND INTEGRATION

Integration is a key point of the ASM having to position elements of different natures within few microns. For this small sub assembly, more than following step by step procedures, the final result is much more dependent of hand skills, adequate tools, and experience of dealing glue with small components. As mentioned above, the integration is carefully considered at the early ASM design phase to minimize the risk of failure. How components must be handled and kept in position during curing of the glue was already addressed in the design of the components and in the related tools.

The production of the ASM module is divided in elementary processes that are performed with the dedicated tools. Due to components sizes and interfaces areas, lots of the steps were done under binocular in clean environment, either to prepare components (cleaning or cables folding) or to apply calibrated amount of glue drops (1 mm^3).

Due to large number of modules to be later produced, most of the tools allow to assemble, align and glue three modules in one shot. This was chosen as a good compromise between tool sizes and required machining accuracy, free volume for handling and positioning parts, glue working lifetime and finally process optimization.

Fig. 13 shows the laboratory and one of the integration benches to adjust and control at the same time the mirror height (sub micron incremental length gauge) and angle (real time laser beam lateral effect sensor) with respect to the piezo base. Fig. 14 shows the positioning of piezo actuators on the piezo base in a narrow space. Fig. 15 shows the counter weight to spread glue evenly in dedicated recess while parts are positioned laterally by stops. Fig. 16 shows the use of gravity during glue curing. The mirrors with respect to the piezo base are this way kept in position over 6 degrees of freedom. Fig. 17 shows the eight modules built for the prototype. Fig. 18 shows the last ASM assembly steps and the temporary covers and mount.

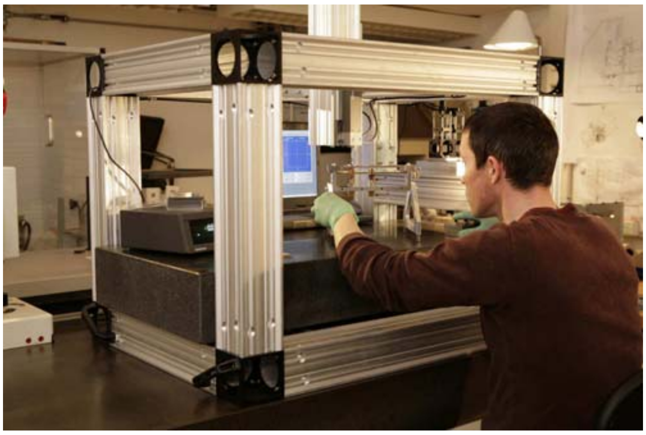

Fig. 13: ASM dedicated bench

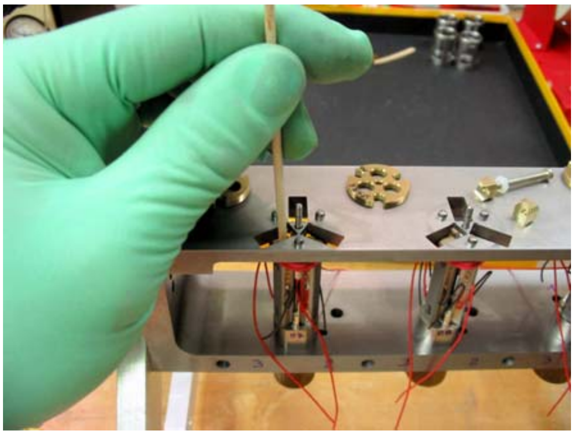

Fig. 14: Hand positioning of piezo actuators on base

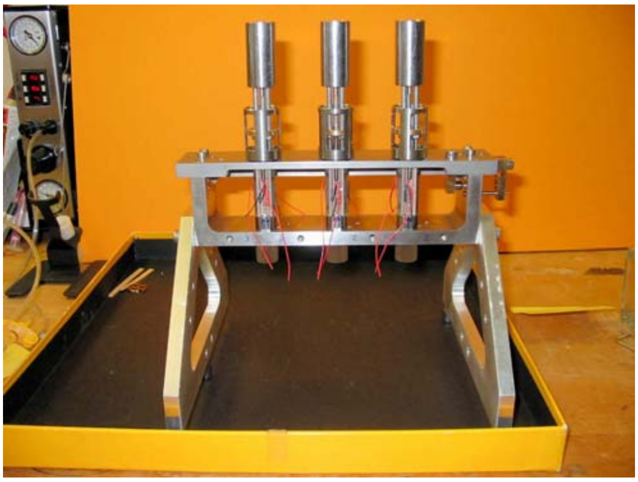

Fig. 15: Counter weight to spread glue evenly in dedicated recess

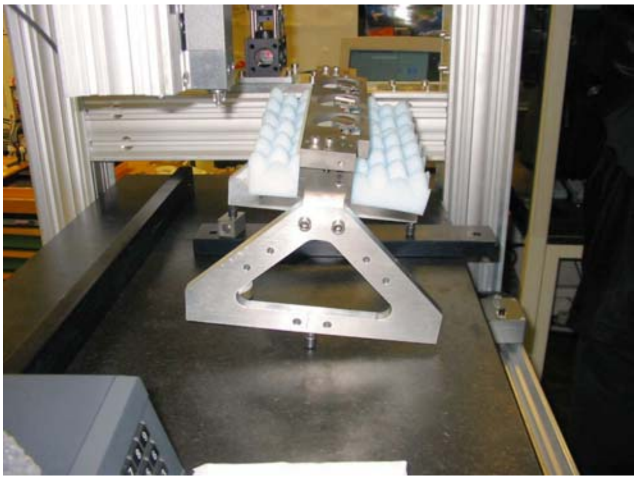

Fig. 16: Use of gravity during glue curing.

Fig. 17: The eight modules ready for building the ASM prototype (considering one spare)

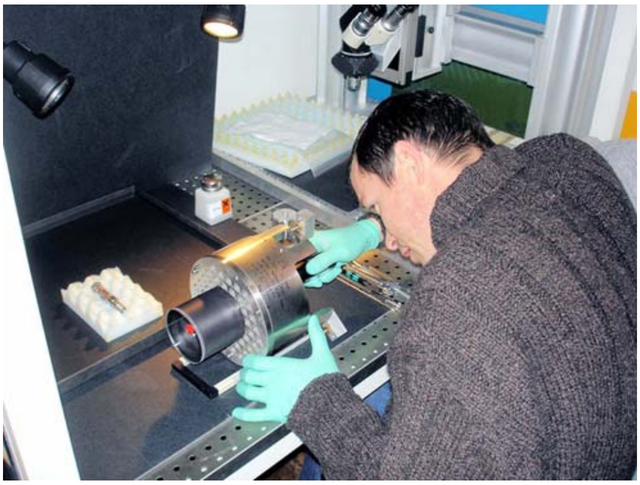

Fig. 18: Module assembly on disk showing the temporary protective covers (dust and high voltage insulation)

5. TEST AND RESULTS

Tests have been carried out at all levels from parts procurement to final ASM prototype assembly (Fig. 19).

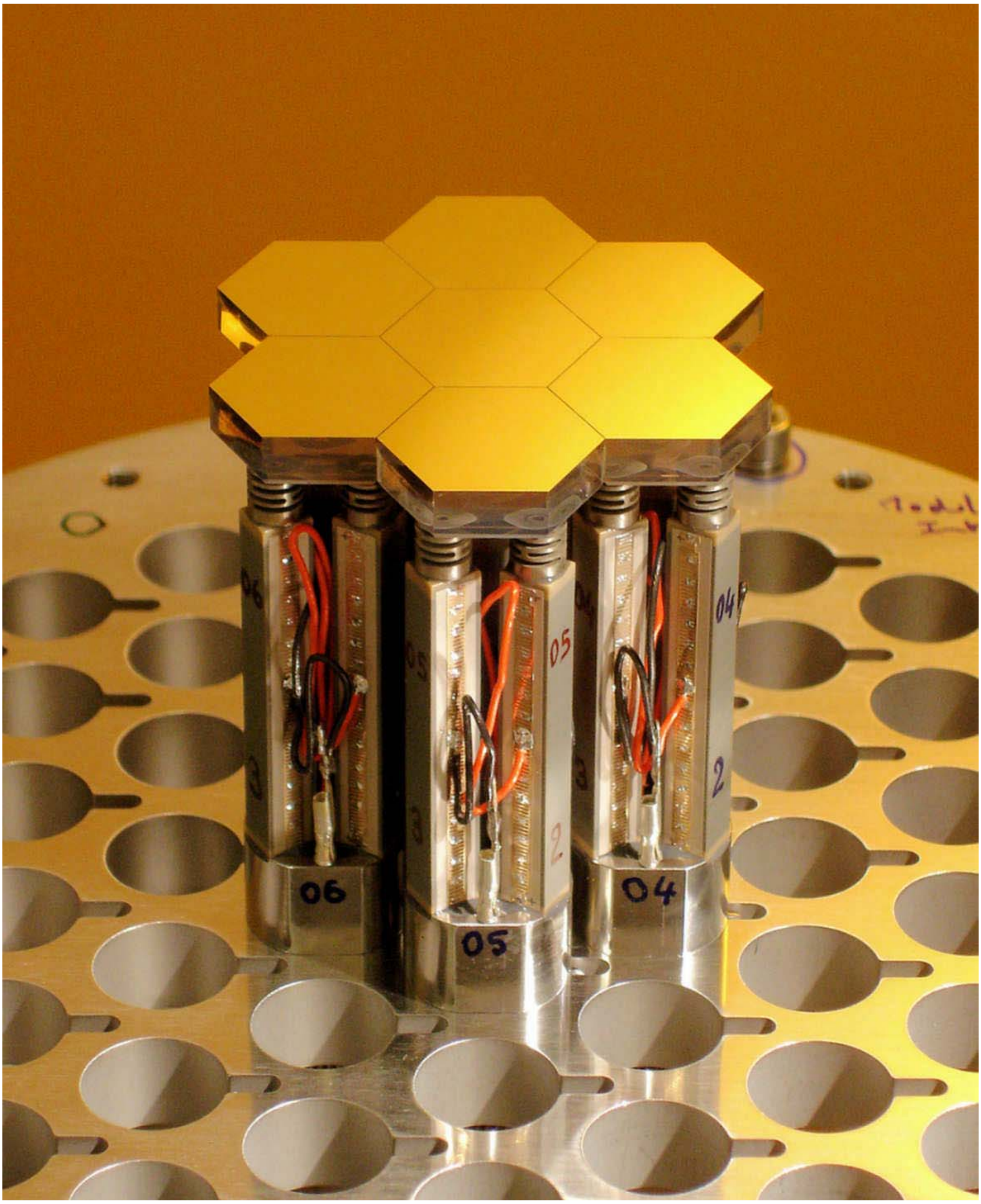

Fig. 19: ASM prototype at rest shown without covers

Prior to proceed with the integration, a campaign of test has been carried out on all single components to first, check that parts were conform to requirements or data sheet and second, to evaluate how they could interact together once assembled.

All mirrors are checked in any aspects from dimensional (Fig. 20) to cosmetic (Fig. 21) and surface flatness (Fig. 22).

Fig. 20: Mirror dimensional measurement

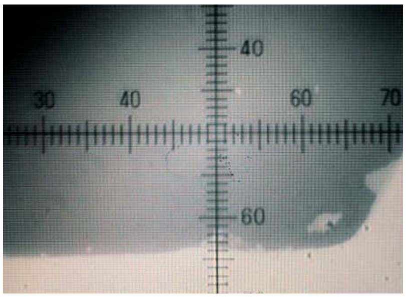

Fig. 21: Mirror cosmetic surface checking

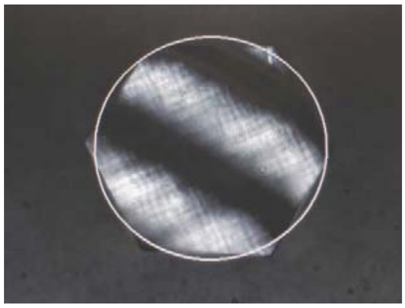

Fig. 22 : Mirror interferogram

Required specifications for the piezo actuator are checked (Fig. 23) on a representative number of parts in order to quantify transversal displacement (5µm max.), axial linearity and hysteresis effect (5% measured) (Fig. 24).

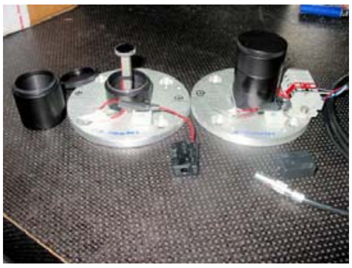

Fig. 23: Piezo actuator prepared for test

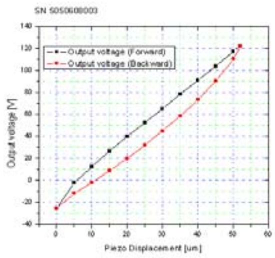

Fig. 24: Piezo actuator hysteresis and linearity measurements

When integrated each module is tested to measure mirror eccentricity with respect to piezo base interface, height and angles of all mirrors between each other, and gap between neighbors (Fig. 25: Test setup, Fig. 26: Image of gap between 3 segments).

Fig. 25: Gap measurement setup

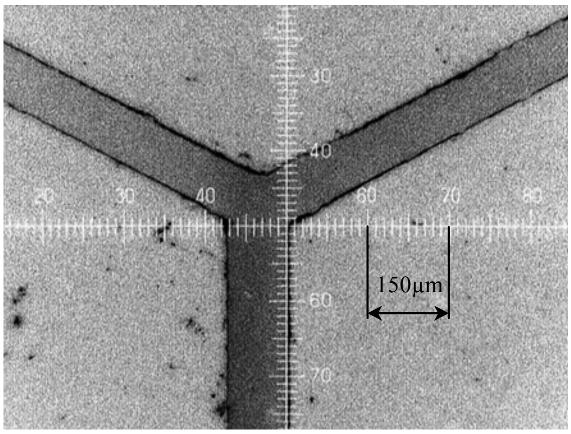

Fig. 26: Gap record

Table 1 summarizes the evolution of mirror surface form: before, after integration and under extreme piezo elongation or tip/tilt configuration. In addition to the surface error, eccentricity of 15 µm is observed and compared to the 20 µm specification; mirror height differences of 7 µm compared to 14 µm specified; surface tilt error of 4 arcmin to be compared to 5 arcmin requested; and gap segment to segment between 79 to 115 µm for a designed range of 100 (+50/-30) µm.

Table 1 : Surface form evolution of mirror before, after integration and under extreme piezo actuator tilt configuration

Module nbr.	WF surface (nm RMS)	Focus (waves)	Astigmatism (waves)		Coma (waves)		Spherical (waves)
			Magnitude	Angle (°)	Magnitude	Angle (°)	
02 Mirror unmounted	7.5	-0.032	0.03	-11.8	0.052	-154.8	-0.091
02 Static after integration	9.6216	-0.0308	0.0237	-21.1	0.0344	35.3	-0.1127
02 120,-20,-20 (V)	13.2297	0.0131	0.0555	-84.8	0.0271	112	0.0079
02 120,120,-20 (V)	15.192	0.0098	0.0542	-66	0.0447	120	0.0021

Soon after prototype integration, dynamical behavior of one module is tested in open loop. As shown in Fig. 27, the first resonance frequency is at around 800 Hz and a second one at around 2000 Hz. These values correspond to the finite element modeling of one module and control simulation. The first resonant frequency is produced by the mirror supports and the second by the constrained piezo-actuator. These two resonance frequencies are well above the maximum working frequency of the ASM (10Hz).

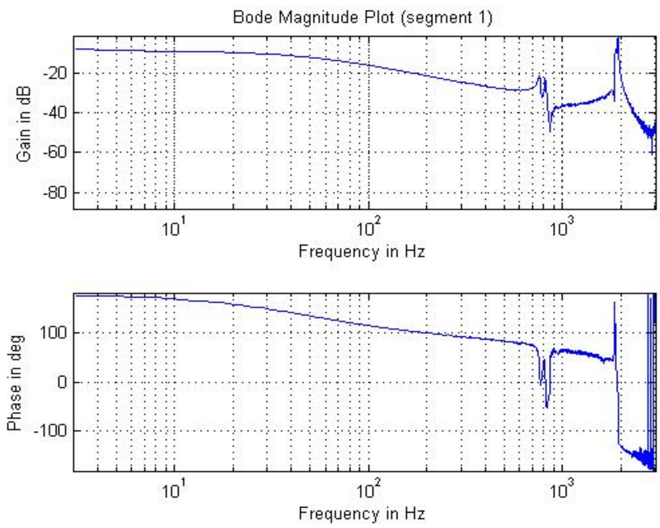

Fig. 27 : Dynamical behavior recording on one integrated piezo actuator

Fatigue tests on several modules are also accomplished without noticeable degradation of the behavior and performance of the system. The three piezo actuators of the modules are driven at maximum amplitude and with a frequency comprised between 5 and 15Hz during more than 48 hours that is representative to the expected lifecycle.

Final verification is to test the Piston, Tip and Tilt functions of the 7 segments prototype in front of an interferometer when coupled to their control electronics. As shown in Fig. 28, the 7 segments may be tipped and tilted independently. In addition one can try to emulate the first phasing of the segments (Fig. 29) as it could be expected in the real case of APE.

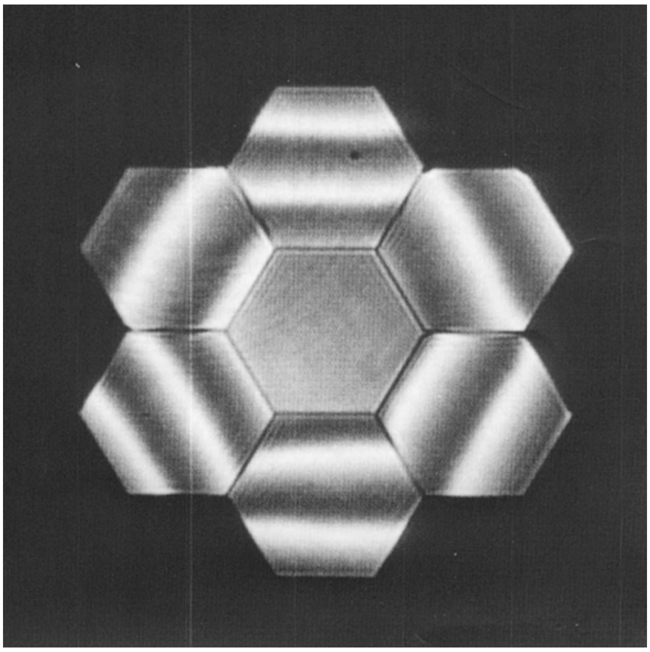

Fig. 28: Independent Tip and Tilt control of modules

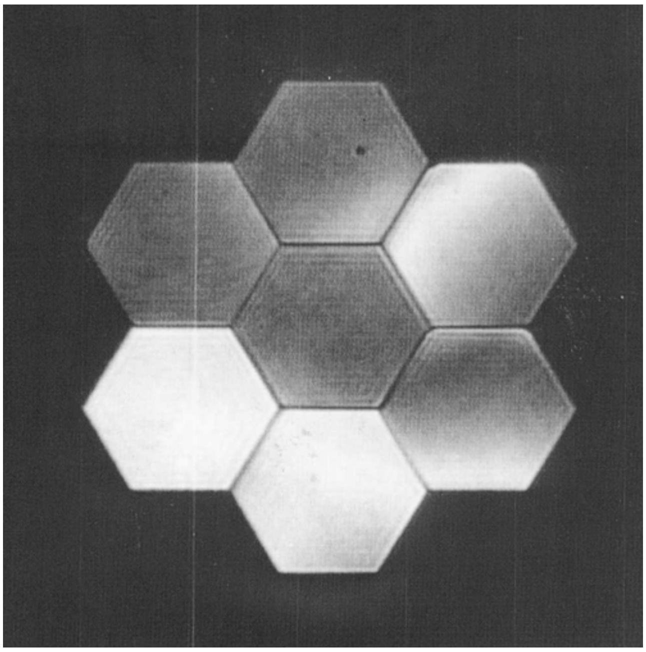

Fig. 29: First ASM prototype phasing emulation

6. CONCLUSION

The concept of the ASM has been proposed in 2004[4] and the design has been finished in 2005. This subsystem was considered as high risk in term of technology and performances. One prototype is manufactured to validate the design, to gain experiences for the procurement and integration and to minimize risks. Test performed on the prototype confirm that the expected performances can be achieved and that the control system can drive the ASM at the required speed and accuracy.

With the experience gained, ESO could detail the design and start the final integration of the nominal ASM. The system will be implemented on APE platform last quarter of this year.

7. ACKNOWLEDGMENTS

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